Relationships between nuisance blooms of *Didymosphenia geminata* and measures of aquatic community composition in Rapid Creek, South Dakota

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Executive Summary

Didymosphenia geminata, an algal species historically inhabiting low-nutrient montane or northern boreal streams, appears to be expanding its geographic range and broadening its environmental tolerances. This diatom was recently identified as an invasive species in New Zealand - the first confirmed record of *D. geminata* in the southern hemisphere (Kilroy, 2004). In the United States, nuisance blooms of *D. geminata* are increasingly reported by the public and media. Nuisance blooms have been observed in Rapid Creek since May 2002 with the greatest mat densities observed just upstream of the community of Hisega.

A stream assessment was conducted to determine the impact of *D. geminata* blooms on the benthic organisms in Rapid Creek. Biological and water quality samples were collected monthly from June through October 2005 at four monitoring sites and from May through October 2006 at five monitoring sites all located between Pactola Reservoir and Canyon Lake. Monitoring is also being conducted in May, August, and October 2007 and is scheduled to resume again in May 2008. This report includes the results and analysis of the years 2005 and 2006 data only, as year 2007 biological sample results are not yet available.

Monitoring sites were categorized as either "impacted" or "non-impacted" by established *D. geminata* mats based on visual observations of areal mat coverage during the 2005 and 2006 monitoring seasons. Nuisance-level growths covering up to approximately 80% of the stream bottom and up to 10 cm thick were observed at sites classified as impacted (RC1, RC2 and RC3), while only small patchy growths of *D. geminata* were observed sporadically at sites classified as non-impacted (RC4 and RC5).

Pactola Reservoir is the source of most of the stream flow in the assessed segment of Rapid Creek. As a result, water quality samples displayed very little variability both spatially and temporally. Water quality is likely not a controlling factor in the occurrence of *D. geminata* blooms in Rapid Creek. No statistically significant differences in water quality parameters were observed between impacted and non-impacted sites. However, two physical parameters, water temperature and stream width, did display statistically significant differences between impacted and non-impacted sites. Impacted sites experienced cooler and less variable water temperatures compared to non-impacted sites, and impacted sites were located in stream channels that were slightly narrower than non-impacted sites.

Several benthic macroinvertebrate and algal metrics were correlated with visual estimates of *D. geminata* areal coverage of the stream bottom, suggesting that impacts to biological communities are directly related to the spatial extent of nuisance blooms. Statistically significant differences in biological metric values were observed between impacted and non-impacted sites. While overall macroinvertebrate abundance was sometimes higher at sites impacted by *D. geminata* blooms, macroinvertebrate diversity and eveness were reduced at impacted sites. Algal biomass measures (chlorophyll *a* and ash-free dry weight) show similar levels of primary productivity among all sites; however, tolerance

of the algal community to pollution was higher at sites impacted by *D. geminata* blooms. These results indicate that nuisance blooms of *D. geminata* have likely altered the taxonomic composition of benthic macroinvertebrate and algal communities in Rapid Creek. Consequently, higher trophic level organisms, such as brown trout, may be affected by shifts in benthic taxonomic composition through food web interactions.

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Background

Didymosphenia geminata is a very distinctive freshwater diatom (Bacillariophyta). It is characterized as one of the larger diatom species with cells exceeding 100 µm in length and 35 µm in width (Kilroy, 2004). Like several other diatoms (e.g. *Cymbella, Gomphonema, and Gomphoneis*), each individual *D. geminata* cell produces a long mucopolysacharide stalk that is fixed to the stream substrate (either stones or plants). This stalk material is produced in great amounts. When nuisance blooms of *D. geminata* develop, dense mats comprised mostly of stalk material are formed. High growth rates and extensive mats of *D. geminata* may impact stream hydrological and ecological processes (Spaulding and Elwell, 2007).

Limited historical information is available on the ecological preferences or environmental tolerances of *D. geminata*. However, some recent descriptions call attention to the ability of *D. geminata* to thrive in clear, oligotrophic (low-nutrient) streams. Stable stream flows and secure substrates allow for the establishment of *D. geminata* colonies. Many reported outbreaks occur in lake-fed or flow-regulated streams (Kilroy, 2004).

These recent accounts help explain the occurrence of *D. geminata* nuisance blooms in Rapid Creek below Pactola Reservoir. Stream flow in Rapid Creek below the reservoir is regulated for the uses of irrigation and drinking water supply. Typically, stream flows in Rapid Creek below Pactola Reservoir are approximately 10 –15 cfs from October through March and usually increase to approximately 40 – 100 cfs during the irrigation season from March through September. Periods of low, stable flow likely allow for the establishment of *D. geminata*, and once established, dense mats can persist throughout the growing season. The reservoir also provides a source of cool water (ranging from roughly 6-12 degrees Celsius during the study period), containing relatively low concentrations of nutrients (average sample total phosphorus concentration during the study period was 0.014 mg/L during the study period).

Nuisance blooms in Rapid Creek have been reported since May 2002 in the stream segment immediately below Pactola Reservoir to approximately 10 km downstream. These recurring blooms persist for several months of the year and can cover a majority of the stream bottom (a maximum of approximately 80% coverage was observed at one monitoring site). Masses of stalk material have been reported by observers as being unsightly and are often mistaken for raw sewage (Figure 1). Home owners along the affected reach of Rapid Creek also complain of stalk material obstructing pump intakes for their irrigation systems.

Figure 1. Stalk material produced by *D. geminata* is resistant to degradation and can persist in streams long after the cells that produced them have expired.   Pictured here are *D. geminata* mats clinging to a boulder along a stream bank of Rapid Creek just below Pactola Reservoir.

D. geminata blooms are expected to affect benthic macroinvertebrate communities through food web interactions and habitat alterations. *D. geminata* affects invertebrate trophic relationships, because invertebrates that are able to readily consume *D. geminata* will be advantaged. Blooms also affect the suitability of the stream habitat for invertebrate communities. For example, invertebrates with a mode of existence that involves clinging to stable substrates may be disadvantaged. Results of biological monitoring conducted in rivers of Colorado indicate that *D. geminata* blooms are related to a decline in total invertebrate richness and a dominance of chironomids or midge fly larvae (Spaulding and Elwell, 2007).

D. geminata blooms are thought to also have a negative effect on fish populations, especially fish that inhabit benthic habitats or consume benthic organisms (Spaulding and Elwell, 2007). Until recently, Rapid Creek has been one of the most productive trout waters in the state. Concurrent with the appearance of *D. geminata* blooms, the brown trout population of the impacted segment of Rapid Creek has experienced a distinct bottleneck with an abundance of juvenile fish and sharp decline of adult fish (SD Department of Game, Fish and Parks, unpublished data).

Methods

Sample Collection Methods

Periphyton and macroinvertebrate samples were collected to provide biological data to examine the relationship of *D. geminata* dominance with the composition of periphyton and macroinvertebrate communities in Rapid Creek. Composite macroinvertebrate periphyton samples were collected semi-monthly at five sites (RC1, RC2, RC3, RC4 and RC5) from May through October 2005 and 2006 (Figure 2). Monitoring at site RC0 was discontinued in 2006 due to difference in water quality, and data from the site is not included in this analysis. Macroinvertebrate samples were collected using Standard Operating Procedures for Field Samplers, Volume II, Biological and Habitat Sampling (SD DENR, 2005), which is an adaptation of US EPA's Environmental Monitoring and Assessment Protocol for Surface Waters (Lazorchak et al., 1998).

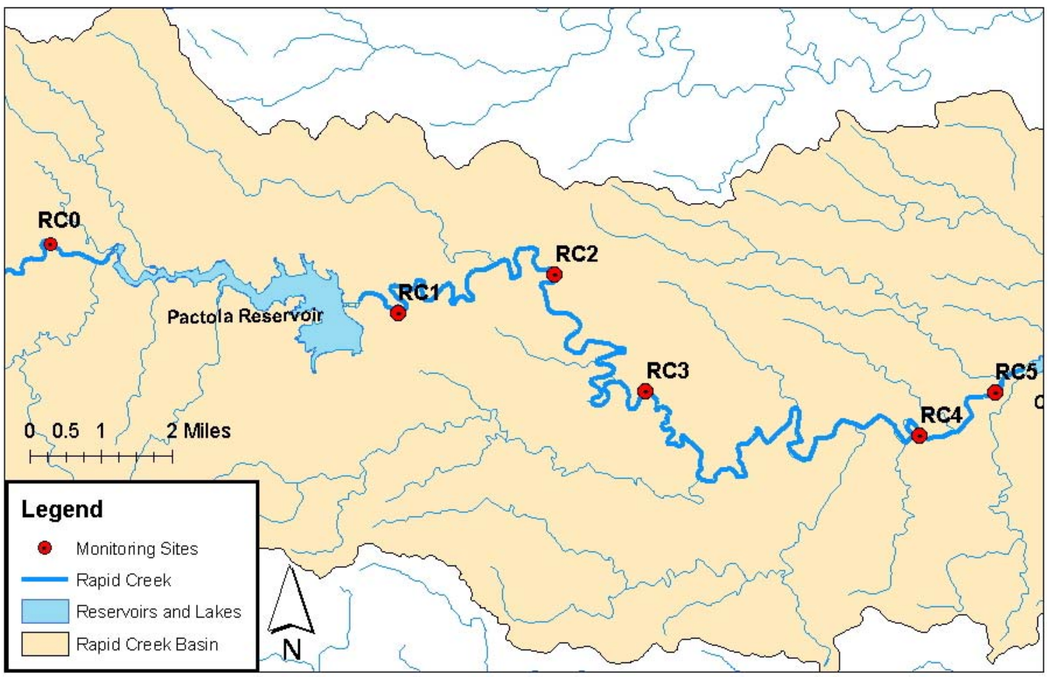

Figure 2. Map of study area showing locations of monitoring sites in Rapid Creek, Pennington County, South Dakota.

During each site visit, the stream bed was visually inspected at eleven transects for the presence of *D. geminata* in order to estimate the percent of stream substrate covered by *D. geminata* and to examine the seasonal variation of *D. geminata* growth. In 2006, a Wolman pebble count was conducted at each site to characterize differences in stream-bottom substrates.

Monthly water quality samples were collected from June through October 2005, and the following parameters were analyzed: alkalinity, ammonia as N, nitrate + nitrite as N, Total Kjeldahl Nitrogen (TKN), total dissolved phosphorus, total phosphorus, total solids, total dissolved solids, total suspended solids, total volatile suspended solids, total organic carbon, calcium, magnesium, sodium, potassium, chloride, sulfate, hardness, and dissolved silicon. Monthly measurements of pH, specific conductivity, dissolved oxygen, and water temperature were also collected with a Yellow Springs Instruments multi-parameter meter.

Data Analysis Methods

Biological samples were not collected prior to the onset of nuisance *D. geminata* blooms. Thus, comparisons were made among Rapid Creek sites similar in water quality but varied in *D. geminata* growth. Monitoring sites were grouped into "impacted" and "non-impacted" sites based on the observed areal coverage of *D. geminata* mats. Sites RC1, RC2, and RC3, categorized as impacted, had established *D. geminata* mats for most of the study period (maximum mat areal coverage over an entire sample reach was approximately 70%); while sites RC4 and RC5, categorized as non-impacted, had very little observable mat growth during the study (only small patches were observed sporadically during few site visits).

Nonparametric statistical tests were chosen for this analysis due to the small sample size and level of precision of the biological measurements and visual observations. A Mann-Whitney U test was used to determine which macroinvertebrate and periphyton metrics were significantly different ($p < 0.05$) between impacted and non-impacted sites. The Spearman Rank Correlation test was used to identify biological metrics that were significantly correlated (Spearman's rank correlation coefficient > 0.6) with percent *D. geminata* coverage. Biological metrics significantly correlated with percent *D. geminata* coverage and significantly different between impacted and non-impacted sites were flagged as potential biological responses to blooms.

Results

Standard algae sample analysis procedures based on a fixed cell count may adequately represent small, abundant organisms. However, the presence of larger, less abundant or rare organisms are often overlooked. Traditional counting procedures greatly underestimate *D. geminata* abundance even in samples collected from nuisance blooms. (Spaulding and Elwell, 2007). As a result, sample abundance of *D. geminata* was very low in all Rapid Creek samples and displayed a weak relationship with visual observations of areal coverage of *D. geminata* mats. Relative sample abundance of *D. geminata* ranged from 0 – 1.7% (mean = 0.5%). Reach-wide average percent *D. geminata* areal coverage ranged from 0.7 – 83% (mean = 46%) at sites classified as impacted and from 0 – 26% (mean = 3.5%) at sites classified as non-impacted (Figure 3).

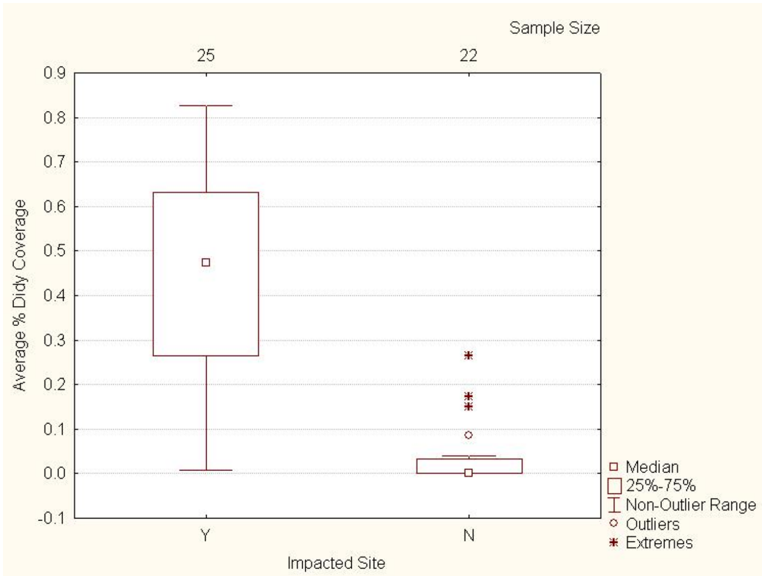

Figure 3. Boxplot of average percent *D. geminata* areal coverage with sites categorized by impact (Y= impacted site; N= non-impacted site).

Macroinvertebrate Community Metrics

For reasons discussed above, relationships between *D. geminata* relative sample abundance and other biological metrics were not statistically significant. However, several macroinvertebrate metrics were significantly correlated with visual observations of percent *D. geminata* areal coverage.

Measures of EPT taxa, organisms belonging to the orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies), were inversely related to *D. geminata* coverage. As the coverage of *D. geminata* increased, the abundance and diversity of EPT taxa decreased. Generally, the presence of EPT taxa indicates high-quality environmental conditions. EPT taxa, particularly the orders Ephemeroptera and Trichoptera, were significantly more abundant and taxonomically rich at non-impacted sites (Figures 4 and 5).

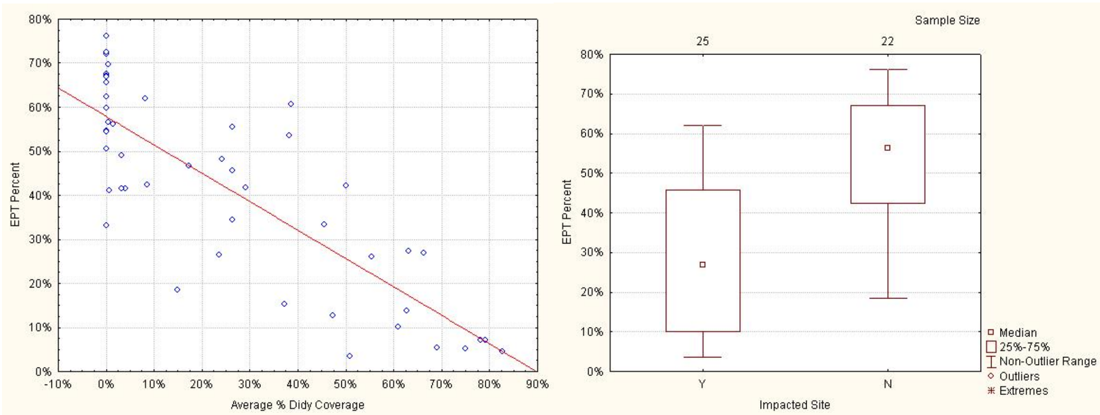

Figure 4. Scatterplot of relative abundance of EPT taxa vs. average percent *D. geminata* areal coverage and boxplot of EPT relative abundance with sites categorized by impact (Mann-Whitney p= 0.00004).

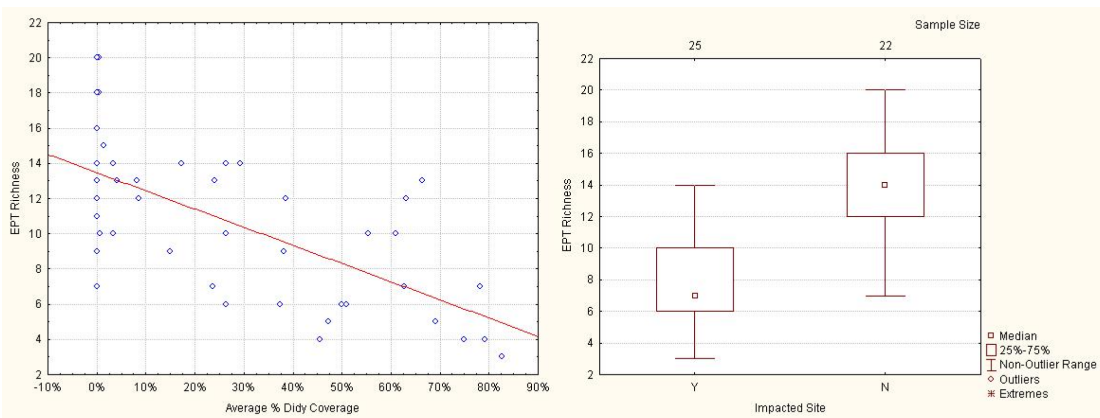

Figure 5. Scatterplot of EPT taxa richness vs. average percent *D. geminata* areal coverage and boxplot of EPT richness with sites categorized by impact (Mann-Whitney p = 0.00002).

Relative abundance of two classes of annelids, Oligochaeta (aquatic worms) and Hirudinea (leeches), was positively correlated with *D. geminata* coverage (Figure 6). The Spearman Rank correlation coefficient was only 0.45; however, the Mann-Whitney test shows that differences in abundance of Oligochaeta and Hirudinea between impacted and non-impacted sites are statistically significant. The most dominant invertebrate species in samples collected from the site with greatest coverage of *D. geminata* was an oligochaete (*Nais sp.*). Algae and other epiphytic material is the main food of many oligochaetes belonging to the family Naididae (Thorp and Covich, 1991).

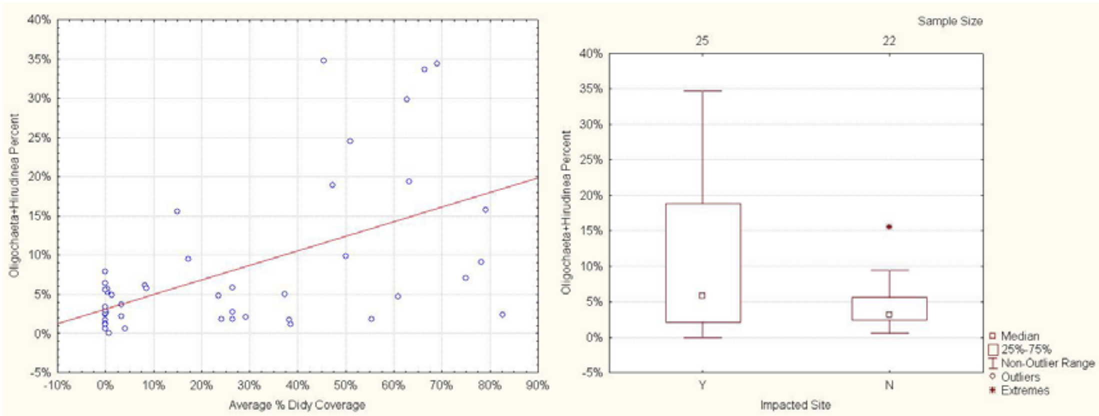

Figure 6. Scatterplot of Oligochaeta and Hirudinea relative abundance vs. average percent *D. geminata* areal coverage and boxplot of Oligochaeta and Hirudinea relative abundance with sites categorized by impact (Mann-Whitney p = 0.0116).

Samples collected from impacted sites also showed a high proportion of mayflies (Ephemeroptera) in the family Baetidae. Baetidae is an abundant family with a wide distribution. Baetid mayflies are small, active swimmers and feed mostly on algae (Thorp and Covich, 1991). Baetid mayflies were always the dominant mayfly family at impacted sites, ranging from 37-100% (mean = 83%) of total mayfly abundance (Figure 7). The large abundance of baetid mayflies is possibly due, in part, to their ability to wade through the dense *D. geminata* stalk material to reach other algae cells and more nutritious organic material. At non-impacted sites, the abundance of this family of mayflies is much more variable and is probably controlled by factors other than *D. geminata* growth.

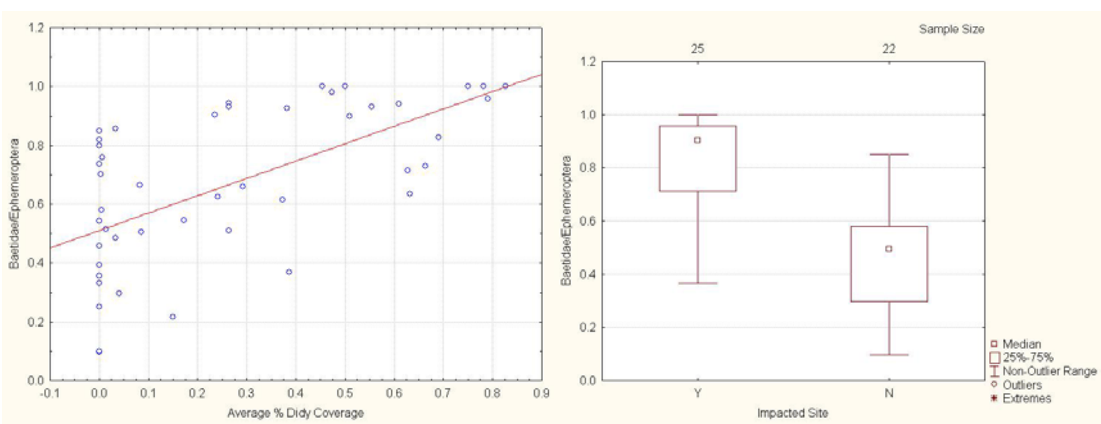

Figure 7. Scatterplot Baetidae:Ephemeroptera vs. average percent *D. geminata* areal coverage and boxplot of Baetidae:Ephemeroptera with sites categorized by impact (Mann-Whitney p = 0.000002).

Tricorythodes range in abundance at non-impacted sites, but they do not occur in high abundance at impacted sites. This mayfly genus decreases exponentially with increasing *D. geminata* coverage (Figure 8). Tricorythodes are larger and less skilled swimmers compared to baetid mayflies, likely affecting their ability to navigate through the dense

D. geminata mats as they gather food. *Tricorythodes* mode of existence is characterized as sprawling over the stream bottom ("sprawlers") or clinging to stable substrates ("clingers").

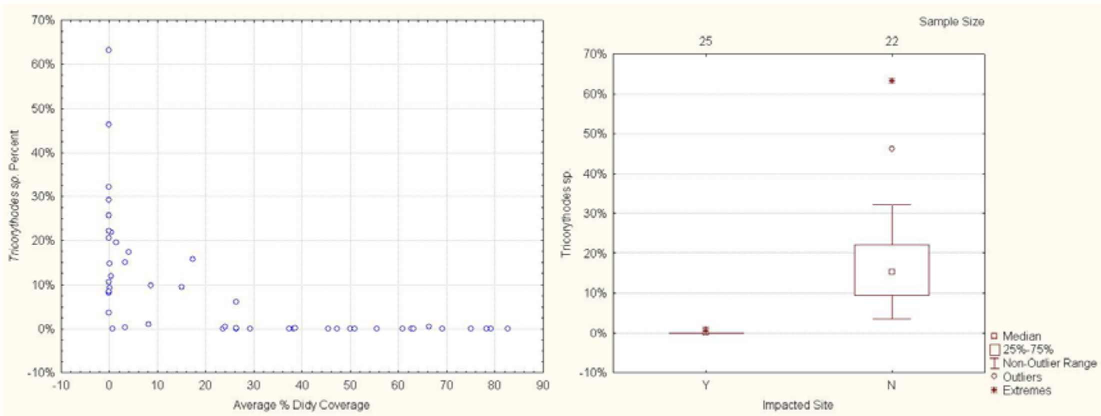

Figure 8. Scatterplot of relative abundance of *Tricorythodes* vs. average percent *D. geminata* areal coverage and boxplot of relative abundance of *Tricorythodes* with sites categorized by impact (Mann-Whitney p = 0.00000001).

D. geminata nuisance blooms may decrease the availability and/or sources of food for macroinvertebrates, and as a consequence, the trophic structure of the biological community is altered. Some invertebrate taxa with specialized feeding strategies were either reduced or absent at impacted sites. The number of macroinvertebrate predator species was inversely related to *D. geminata* coverage (Figure 9). This functional feeding group may suffer in the presence of dense algal mats, where their mobility, or the mobility of their prey, might be reduced.

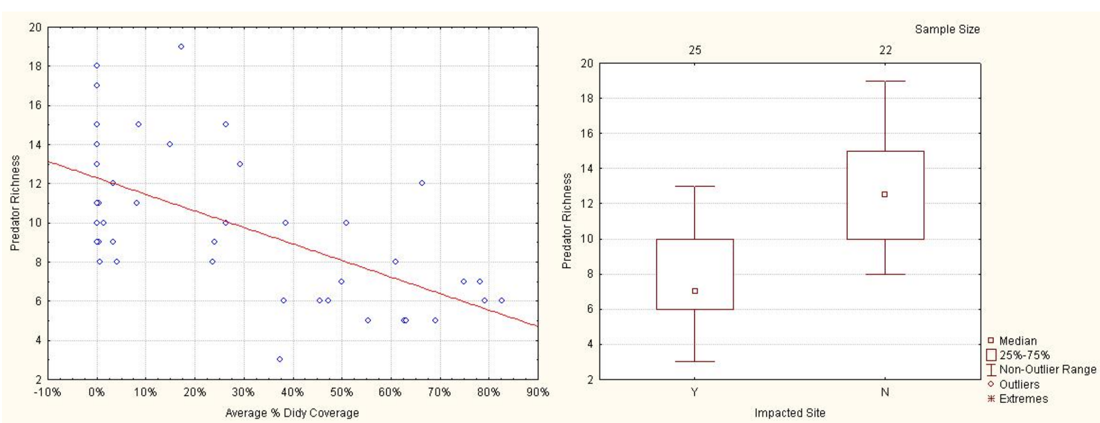

Figure 9. Scatterplot of macroinvertebrate predator richness vs. average percent *D. geminata* areal coverage and boxplot of relative abundance of Gomphidae with sites categorized by impact (Mann-Whitney p = 0.000001).

Odonates (dragonflies), for example, were not observed at impacted sites. However, at non-impacted sites, the dragonfly family Gomphidae was present. Other invertebrate predators, such as the trichopteran *Oecetis sp*., were also lacking at sites impacted by nuisance blooms. Although abundance of *Oecetis sp.* was proportionally low among all samples, relative abundance decreased as percent *D. geminata* coverage increased.

D. geminata blooms may also affect the composition of the macroinvertebrate community by altering the stream habitat. The number of macroinvertebrate species characterized as "clingers" were significantly reduced at impacted sites. Clingers have behavioral (e.g. construction of fixed retreats) and morphological (e.g. claws and flattened bodies) adaptations for attachment to surfaces in swift-flowing water, but they require a stable substrate for attachment. Thus, clingers may be negatively impacted due to the loss of suitable habitat. Not only do nuisance blooms physically cover the stream bottom, reducing the amount of accessible stable substrate, the mats also trap fine sediment that can settle and embed the larger cobble and gravel substrates.

Up to 30 clinger taxa were observed at non-impacted sites, and as few as six clinger taxa were present at impacted sites (Figure 10). While the lowest clinger taxonomic richness occurred at a site categorized as impacted, *D. geminata* mats were not observed at the site at the time the sample was collected. However, less than one month prior to the collection of this sample, approximately 37% of the stream bottom at this site was covered by *D. geminata* mats. This may indicate that the effects of nuisance blooms on macroinvertebrate communities can persist even after the mats are no longer visible.

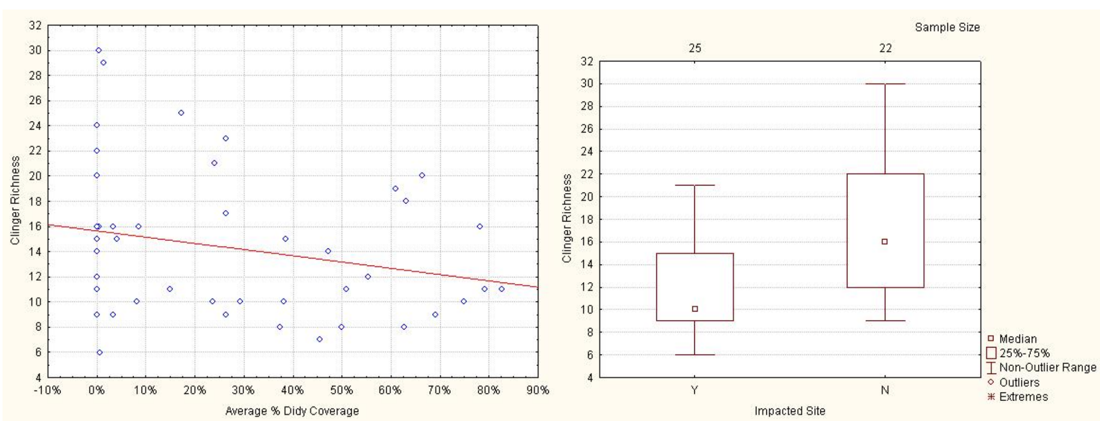

Figure 10. Scatterplot of clinger richness vs. average percent *D. geminata* areal coverage and boxplot of clinger richness with sites categorized by impact (Mann-Whitney p = 0.000005).

Measures of biological community diversity and eveness show that sites impacted by *D. geminata* blooms have lower overall numbers of macroinvertebrate species and dominant species comprise a large proportion of the total number of sampled organisms. Macroinvertebrate taxa richness was inversely related to percent *D. geminata* coverage and was significantly reduced at impacted sites (Figure 11). The relative percent abundance of the top ten most dominant taxa was directly related to spatial extent of *D. geminata* coverage, and often significantly higher at impacted sites (Figure 12). In other words, abundance of the top ten most dominant species accounts for a larger percentage of the total sample abundance at impacted sites than non-impacted sites. In a majority of the samples, the dominant macroinvertebrate taxon was a mayfly (Baetidae). However, in samples collected from the most severely impacted site (RC2), the dominant macroinvertebrate taxon was an aquatic worm (Naididae).

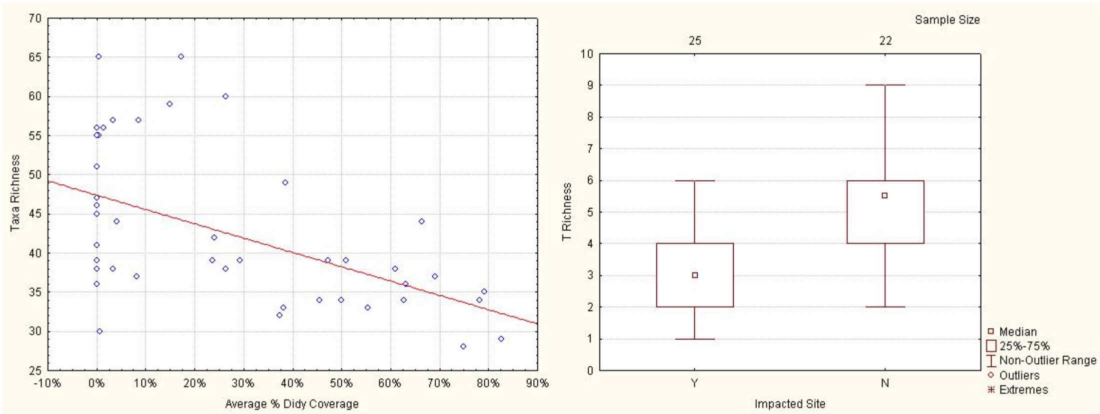

Figure 11. Scatterplot of macroinvertebrate species richness vs. average percent *D. geminata* areal coverage and boxplot of macroinvertebrate species richness with sites categorized by impact (Mann-Whitney p = 0.0127).

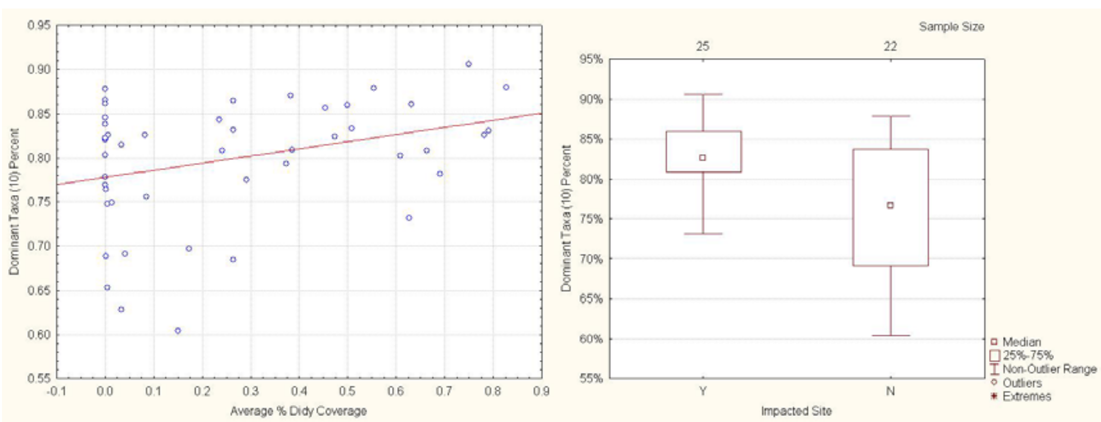

Figure 12. Scatterplot of the relative abundance of the top ten dominant taxa vs. average percent *D. geminata* areal coverage and boxplot of relative abundance of the top ten dominant taxa with sites categorized by impact (Mann-Whitney p = 0.0064).

Principle components analysis (PCA) was used to determine how similar or dissimilar the macroinvertebrate communities were among monitoring sites. PCA resulted in 46 principle components. The first two components explained approximately 30% of the variability of the macroinvertebrate community data. When sample PCA factor coordinates are plotted for factors 1 and 2, the samples appear clustered into two distinct groups (Figure 15). These clusters match the site impact classifications made based on the visual assessment of *D. geminata* cover. Samples with positive factor 1 values were collected from impacted sites (RC1, RC2 and RC3), while samples with negative factor 1 values were collected at non-impacted sites (RC4 and RC5). In addition, samples collected from impacted sites are clustered more tightly compared to non-impacted sites, showing the lower diversity of the macroinvertebrate communities at impacted sites.

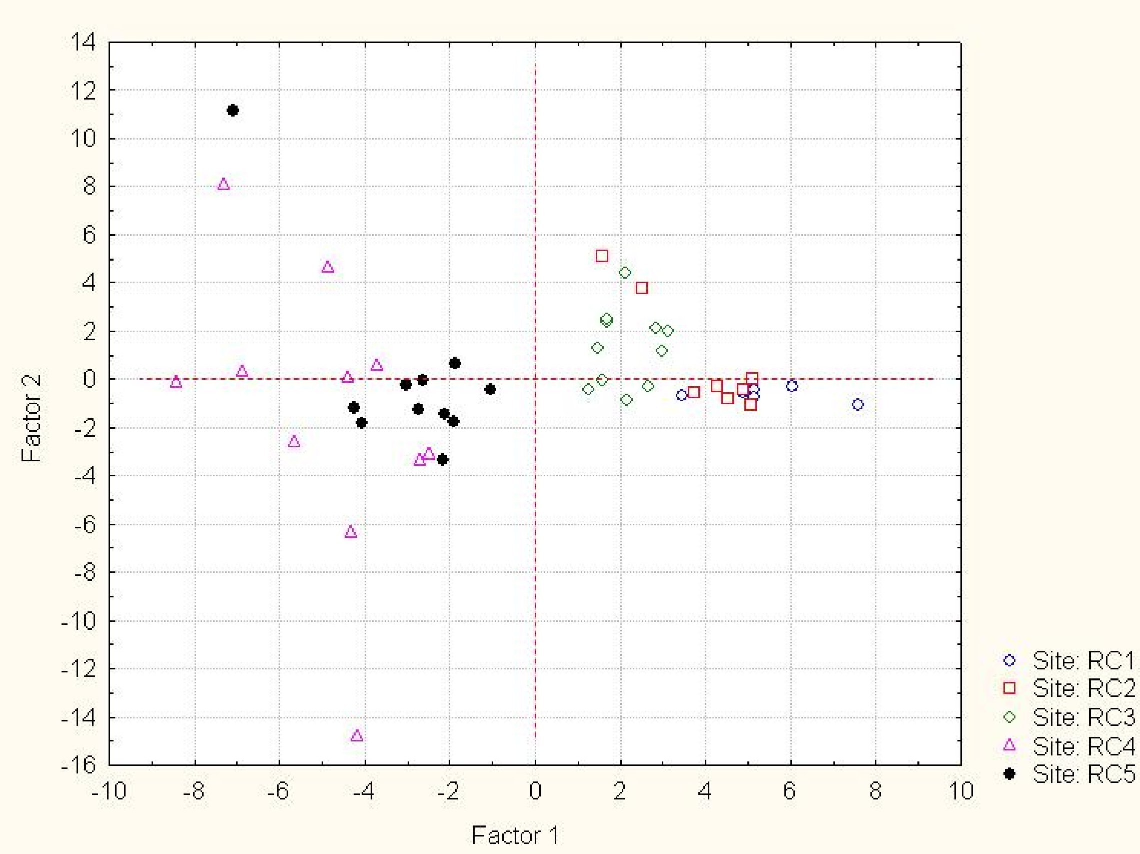

Figure 13. Sample factor coordinates plotted for PCA factors 1 and 2 (both factors combined account for 28% of the variability in the macroinvertebrate community relative abundance data).

Relative abundance of several chironomid genera (e.g. *Pagastia sp*. and *Micropsectra sp*.) displayed strong positive correlations with factor 1, while relative abundance of several trichopteran and coleopteran genera (e.g. *Brachycentrus sp*., *Hydropsyche sp*., *Microcylloepus sp.,* and *Zaitzevia sp*.) displayed strong negative correlations with factor 1. Relative abundance of two chironomid genera, *Cricotopus sp*. and *Paralauterborniella sp*., displayed the strongest positive correlations with factor 2, while relative abundance of two odonate genera, *Aeshna sp.* and *Coenagrion/Enallagma sp.,* displayed strong negative correlations with factor 2.

The macroinvertebrate sampling protocol used for this assessment (multi-habitat, composite sample collected with a kicknet) provides "semi-quantitative" information, given the low precision of the area sampled compared to other, more quantitative, samplers (e.g. Surber or Hess samplers). In addition, the kick net procedure does not guarantee that all organisms in the area sampled will drift into the net. Thus, measures of total macroinvertebrate sample abundance are not precise. Nonetheless, estimates of total sample abundance were calculated, based on sub-sample proportions, to provide for general comparisons of secondary productivity among monitoring sites.

Estimates of total macroinvertebrate abundance were more variable at impacted sites than non-impacted sites. The most abundant sample was collected from an impacted site, while the least abundant was collected from a non-impacted site (Table 1). However, differences in total sample abundance between impacted and non-impacted sites were not statistically significant (Mann-Whitney p = 0.1758). In addition, total organism abundance provides only a coarse measure of productivity, as differences in organism size among sites can influence how well abundance is correlated with more direct measures of productivity. The most abundant sample was predominantly comprised of small aquatic worms and midges, while the least abundant sample was comprised mainly of elmid beetle larvae.

Table 1. Descriptive statistics of estimated total macroinvertebrate sample abundance categorized by impact.

Site Category	Valid N	Median	Mean	Minimum	Maximum	Std.Dev.
Non-impacted	22	2,848	3,912	675	14,784	3,304
Impacted	25	4,111	5,538	741	19,140	4,742

Periphyton Community Metrics

Only two algal community metrics, relative abundance of cosmopolitan taxa and the diatom Pollution Tolerance Index, displayed significant correlations with coverage of *D. geminata* and were statistically different between impacted and non-impacted sites. Cosmopolitan diatom taxa are those characterized as widely distributed in the Northern Hemisphere, tolerant of wide ranges of ecological conditions, and aggressive opportunists (capable of out-competing other species, including native species) (W. Bollman, pers. comm.). Cosmopolitan taxa were relatively abundant at all sites, but were often more abundant at impacted sites than non-impacted sites (Figure 14).

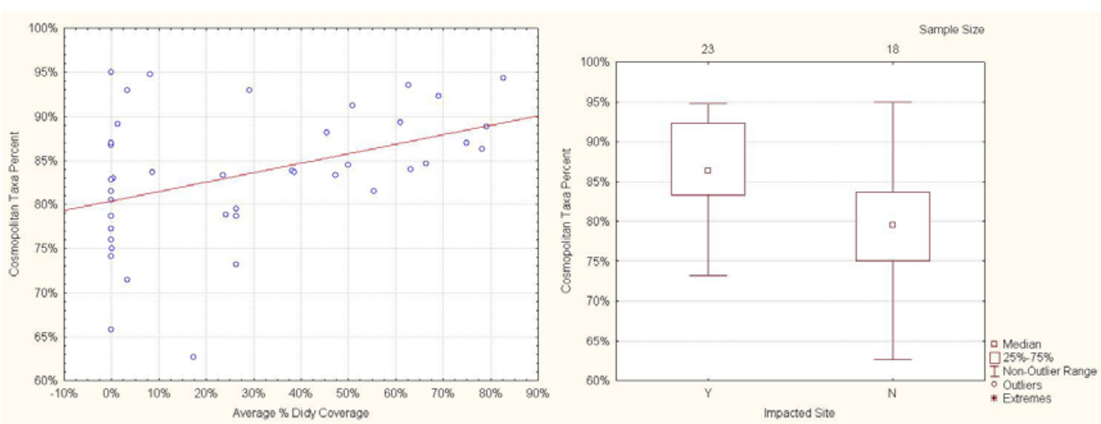

Figure 14. Scatterplot of the relative abundance cosmopolitan taxa vs. average percent *D. geminata* areal coverage and boxplot of relative abundance of cosmopolitan taxa with sites categorized by impact (Kruskal-Wallis p = 0.0021).

The Pollution Tolerance Index (PTI) was calculated for each diatom sample. To determine an index score, diatoms are grouped into three categories according to their tolerance to increased pollution. The PTI ranges from a value of 1 for most polluted to 3 for least polluted (Barbour et al., 1999). PTI scores were inversely related to coverage of nuisance blooms. Differences in PTI values between impacted sites and non-impacted sites were not significantly different, and all sample values indicate diatom communities that are sensitive to pollution. Still, lowest PTI values were observed at impacted sites (Figure 15). Results of this metric indicate that diatom assemblages at impacted sites may be slightly more tolerant to pollution.

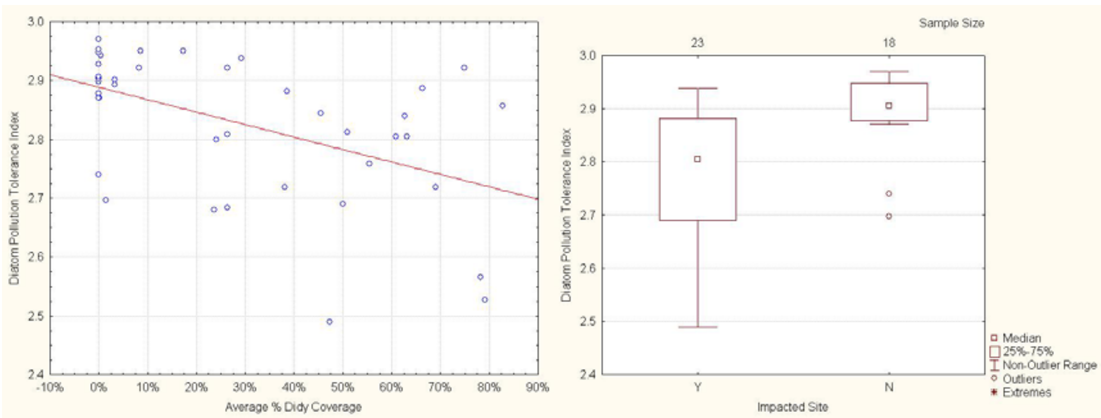

Figure 15. Scatterplot of diatom Pollution Tolerance Index (PTI) vs. average percent *D. geminata* areal coverage and boxplot of diatom PTI with sites categorized by impact (Kruskal-Wallis p = 0.5839). The PTI scale ranges from one to three with values increasing as the pollution tolerance of the diatom community decreases.

Measures of periphyton biomass (chlorophyll and ash-free dry weight) were not correlated with coverage of *D. geminata* and were not statistically different between impacted and non-impacted sites. Macroinvertebrate sample abundance was neither correlated with chlorophyll nor AFDW measurements from periphyton samples. However, maximum AFDW at impacted sites was nearly twice the maximum value at non-impacted sites, and maximum chlorophyll *a* concentration at impacted sites was roughly three times the maximum concentration at non-impacted sites (Table 2).

Table 2. Minimum and Maximum ash-free dry weight (AFDW) and chlorophyll *a* (chlor. *a*) of periphyton samples collected from impacted and non-impacted sites during the 2005 and 2006 monitoring seasons.

Site Category	Number of Samples (n)	AFDM (g/m^2) min.	AFDM (g/m^2) max.	Chlor. *a* (mg/m^2) min.	Chlor. *a* (mg/m^2) max.
Impacted	25	0	75.23	1.03	153.81
Non-impacted	21	3.22	42.88	0	54.98

Chlorophyll may be a poor measure of biomass where large masses of *D. geminata* mats are present, because the mats are comprised mostly of stalk material with only a thin surface layer of cells containing chlorophyll (Larned et al., 2006). Barbour et al. (1999) indicates that chlorophyll *a* levels >100 mg/m^2 or areal macroalgae coverage >40% are considered nuisance levels of algal biomass. Only three chlorophyll samples were greater than 100 mg/m^2, but several visual measurements of *D. geminata* coverage at impacted sites exceeded 40%.

Water Quality

Water quality constituents displayed little variability during the study period (see Appendix B for boxplots of water quality data grouped by monitoring site). Of all physical and chemical properties of Rapid Creek measured, only stream temperature and average stream width were statistically different between impacted and non-impacted sites (Tables 3 and 4). Instantaneous water temperature measurements were collected at each site during sampling visits. Instantaneous water temperature was higher and more variable at non-impacted sites compared to impacted sites. Stream width measurements at impacted sites ranged from 7.4 – 12.3 m (mean = 9.8), while stream width measurements at non-impacted sites ranged from 7.5 – 15.4 m (mean = 12.0).

Table 3. Descriptive statistics of water quality parameters for samples collected at impacted sites (sites RC1, RC2 and RC3).

Parameter	Valid N	Mean	Median	Min	Max	Std.Dev.
Ammonia, mg/L	25	0.01	0.01	0.01	0.01	0.00
Bicarbonate, mg/L	12	192	193	183	197	4.42
Carbonate, mg/L	12	<5	<5	<5	5	1.13
Dissolved calcium, mg/L	25	43	43	39	47	2.03
Dissolved chloride, mg/L	25	3.8	<5	<5	6.0	1.04
Dissolved magnesium, mg/L	25	23	24	21	25	1.01
Dissolved oxygen, mg/L	23	11.2	11.2	8.3	13.2	1.00
Dissolved phosphorous, mg/L	25	0.006	0.005	<0.002	0.017	0.00
Dissolved potassium, mg/L	25	2.6	2.7	2.1	3.0	0.25
Dissolved silicon, ug/L	25	4	4	3	4	0.33
Dissolved sodium, mg/L	25	3.3	3.3	2.7	4.2	0.40
Dissolved sulfate, mg/L	25	46	47	37	50	3.43
Hardness, mg/L	25	204	207	190	220	8.57
Nitrate, mg/L	25	0.06	<0.1	<0.1	0.13	0.03
Nitrite, mg/L	12	<0.1	<0.1	<0.1	<0.1	0.00
pH, standard units	19	8.40	8.43	7.95	8.79	0.24
Specific conductance, umho/cm	23	385	388	357	401	10.60
Total alkalinity, mg/L as $CaCO_3$	22	162	163	150	168	3.57
Total dissolved solids, mg/L	16	237	237	210	251	11.35
Total Kjeldahl nitrogen, mg/L	25	0.3	<0.5	<0.5	0.6	0.09
Total phosphorous, mg/L	25	0.010	0.009	0.004	0.023	0.00
Total solids, mg/L	25	239	240	210	255	12.04
Total suspended solids, mg/L	25	4	<5	<5	11	2.72
Total volatile solids, mg/L	25	2	<1	<1	6	1.48
Water temperature, degrees Celsius	23	9.30	9.24	4.97	13.72	1.77

Table 4. Descriptive statistics of water quality parameters for samples collected at non-impacted sites (sites RC04 and RC05).

Parameter	Valid N	Mean	Median	Min	Max	Std.Dev.
Ammonia, mg/L	22	0.01	0.01	0.01	0.01	0.00
Bicarbonate, mg/L	8	191	192	180	202	7.54
Carbonate, mg/L	8	4	<5	<5	7	1.75
Dissolved calcium, mg/L	22	43	43	36	47	2.35
Dissolved chloride, mg/L	22	4.4	<5	2.8	5.9	1.01
Dissolved magnesium, mg/L	22	23	23	22	25	0.88
Dissolved oxygen, mg/L	18	10.6	10.7	8.5	13.2	1.20
Dissolved phosphorous, mg/L	22	0.007	0.007	<0.002	0.016	0.00
Dissolved potassium, mg/L	22	2.6	2.6	2.3	3.4	0.25
Dissolved silicon, ug/L	22	4	4	3	9	1.05
Dissolved sodium, mg/L	22.0	3.6	3.5	2.6	5.3	0.57
Dissolved sulfate, mg/L	22	45	46	35	49	3.58
Hardness, mg/L	22	204	201	180	240	12.35
Nitrate, mg/L	22	0.06	<0.1	<0.1	0.10	0.02
Nitrite, mg/L	8	<0.1	<0.1	<0.1	<0.1	0.00
pH, standard units	14	8.46	8.43	7.96	8.89	0.25
Specific conductance, umho/cm	18	385	387	333	424	22.90
Total alkalinity, mg/L as $CaCO_3$	20	161	162	156	166	3.05
Total dissolved solids, mg/L	16	237	238	210	250	11.15
Total Kjeldahl nitrogen, mg/L	22	0.4	<0.5	0.2	2.3	0.44
Total phosphorous, mg/L	22	0.012	0.008	0.004	0.100	0.02
Total solids, mg/L	22	240	241	210	270	14.90
Total suspended solids, mg/L	22	4.0455	2.5000	<5	10.0000	2.66
Total volatile solids, mg/L	22	0.9091	<1	<1	3.0000	0.81
Water temperature, degrees Celcius	18	12.55	13.73	4.51	18.01	3.94

Continuous temperature loggers were deployed at sites RC1, RC3 and RC5 during the 2006 monitoring season. As expected, the most downstream site (RC5) displayed significantly higher water temperatures during the month of July 2006 compared to the most upstream site (RC1). Water temperature was more variable at site RC3 compared to both sites RC1 and RC5, possibly due to differences in shading, stream channel morphology or the position of the temperature probe (Figure 16).

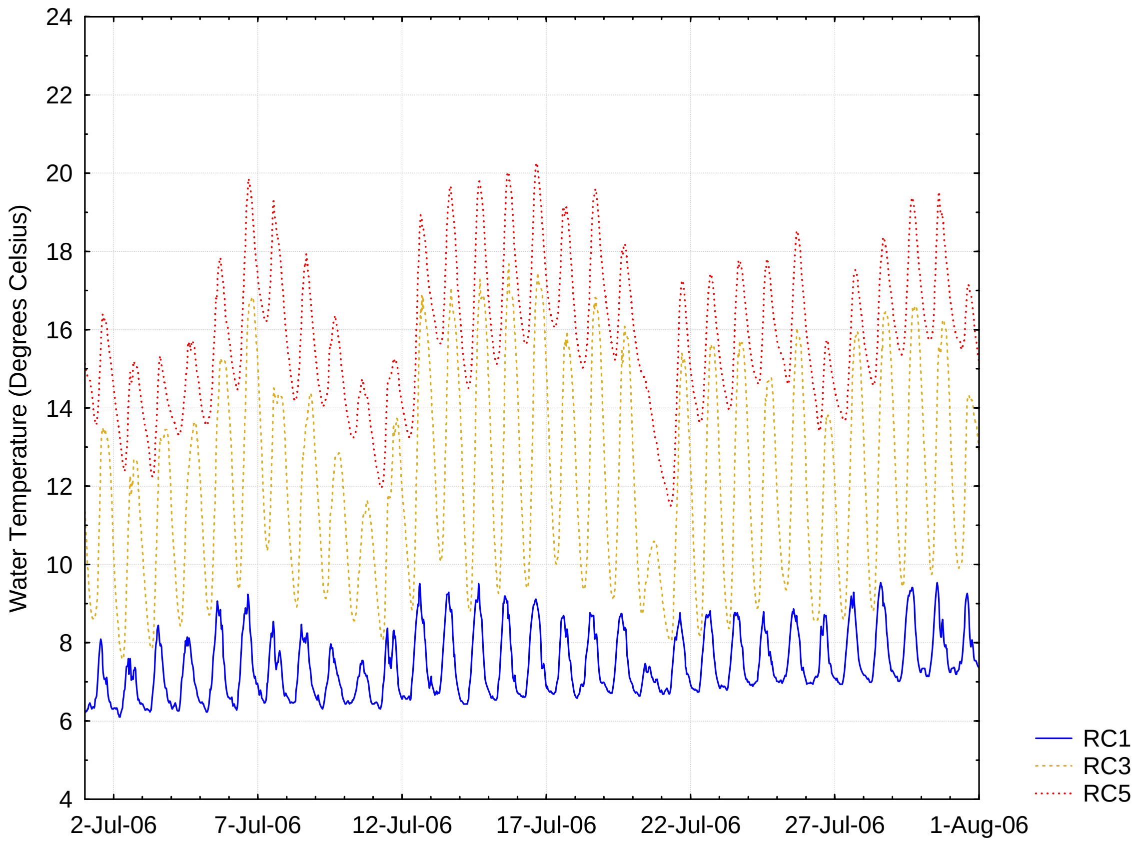

Figure 16. Continuous water temperature data collected at 15-minute intervals during the month of July 2006 from three sites (RC1, RC3 and RC5) in Rapid Creek, South Dakota.

Observed differences in the composition of the macroinvertebrate and periphyton communities among monitoring sites are not likely driven by the slight variations in water quality constituents or physical parameters measured during this assessment. Water temperature is an important factor in shaping the macroinvertebrate and periphyton communities of aquatic systems. However, observed differences in the invertebrate and periphyton communities between impacted and non-impacted sites are probably not driven by water temperature or stream width. Sites impacted by nuisance blooms were found in narrower channels and experienced cooler water temperatures, but they also appear to accommodate less desirable biological communities compared to non-impacted sites. Generally, invertebrate and periphyton communities indicative of good biological health would be found in cool, narrow streams, rather than warm streams with wide channels.

Conclusions

Proliferations of *D. geminata* may cause a disruption of trophic interactions and alter the stream habitat to such a degree that sensitive organisms may be greatly reduced or excluded from the site. Results of this monitoring effort indicate that macroinvertebrate and periphyton communities are negatively affected by *D. geminata* nuisance blooms.

D. geminata blooms may have changed the composition of the periphyton community of impacted reaches of Rapid Creek, resulting in communities with more cosmopolitan diatoms and greater tolerance to pollution. Measures of primary production were not statistically different between impacted and non-impacted sites and were not correlated to visual measures of *D. geminata* coverage. Chlorophyll *a* concentrations do not correlate well with areal coverage because *D. geminata* produces proportionally much more stalk material than cells, and only the cells contain chlorophyll. Maximum AFDW measured at impacted sites was nearly double the maximum AFDW at non-impacted sites. Maximum chlorophyll a concentrations impacted sites were roughly three times the concentrations measured at non-impacted sites. Still, a visual assessment of *D. geminata* coverage was the only biomass measure displaying significant correlations with benthic community metrics. Visual estimates of coverage appear to best account for the large amount of stalk material produced by *D. geminata*.

Macroinvertebrate communities at sites impacted by *D. geminata* blooms were less even and less diverse than at non-impacted sites. Abundance and diversity of sensitive macroinvertebrate groups, such as EPT taxa, were inversely related to coverage of blooms. The orders Ephemeroptera (mayflies) and Trichoptera (caddisflies) were significantly more abundant and taxonomically rich at non-impacted sites than at impacted sites. These macroinvertebrate groups appear to be replaced by more tolerant midges and aquatic worms at impacted sites. Mayflies and caddisflies were the most common invertebrate groups found in trout stomachs in a New Zealand study, comprising 80% of the total trout diet (Hayes et al., 2006). In Rapid Creek, losses of these larger invertebrate species at impacted sites may have caused the significant reduction of adult brown trout.

D. geminata blooms can affect stream habitat quality directly by occupying almost all stable benthic substrate and indirectly by trapping fine sediment that fills interstitial spaces that are typically inhabited by invertebrates. Numbers of species characterized as “clingers” were lower in samples collected from impacted sites than non-impacted sites, most likely due to the lack of stable substrate. Invertebrates tolerant of fine sediment, such as aquatic worms, were more abundant at impacted sites.

Results indicate that overall macroinvertebrate abundance was not significantly affected by *D. geminata* blooms. While the maximum estimated sample abundance was observed at an impacted site, differences in abundance between impacted and non-impacted sites were not statistically significant. However, many of the relatively larger-sized macroinvertebrate groups (e.g. mayfly, caddisfly, and dragonfly larvae) observed at non-impacted sites were reduced or absent at impacted sites. Thus, macroinvertebrate biomass may be lower at impacted sites due to the loss of relatively larger species. Quantitative macroinvertebrate sampling procedures and size-class or dry weight analyses of macroinvertebrate communities would be required to verify this conclusion.

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Appendix A. Glossary

benthic
Located on the bottom of a body of water or in the bottom sediments, or pertaining to bottom-dwelling organisms.

biomass
The total quantity, at a given time, of living organisms of one or more species usually expressed in weight per unit area.

boreal
Of or relating to the cool temperature regions of Northern Hemisphere.

diatom
A major group of eukaryotic algae and one of the most common types of phytoplankton. Most diatoms are unicellular, although some form chains or simple colonies. A characteristic feature of diatom cells is that they are encased within a unique cell wall made of silicate.

macroinvertebrate
An invertebrate that is visible to the naked eye, such as an insect, snail or worm.

montane
Of, relating to, growing in, or being the biogeographical zone of relatively moist, cool upland slopes below the timberline, often dominated by large coniferous trees.

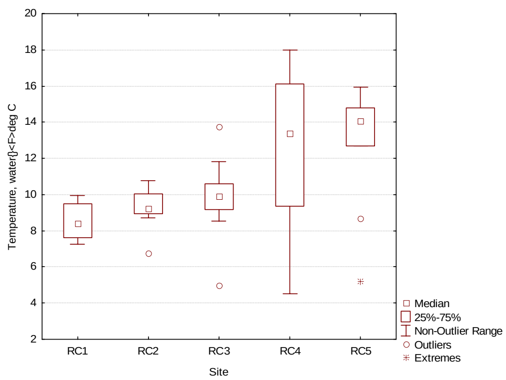
nuisance bloom (algae)
An unusual, sudden or excessive abundance of algae. A deviation from the normal cycle of algal biomass.

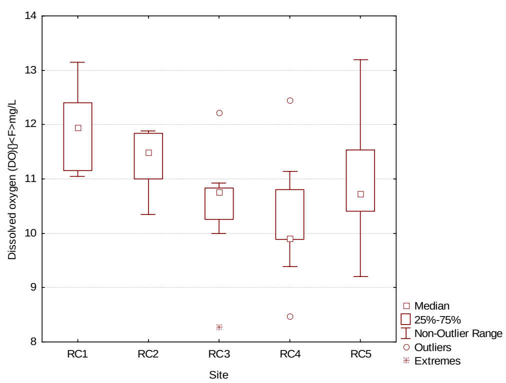
periphyton
Algae attached to an aquatic substrate; also known as benthic algae.

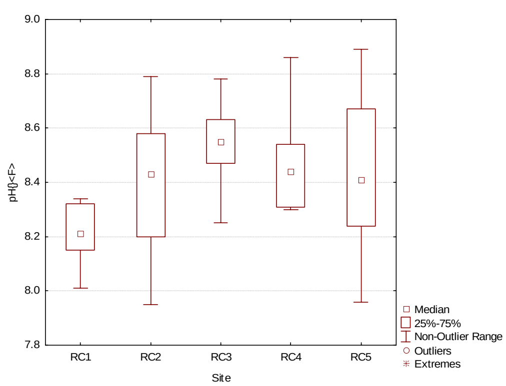
trophic
Relating to processes of energy and nutrient transfer from one or more organisms to others in an ecosystem.

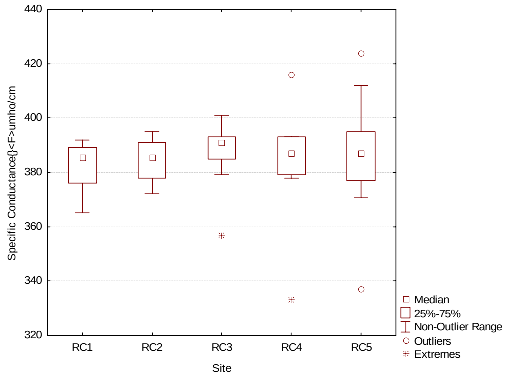
Appendix B. Water Quality Parameter Boxplots

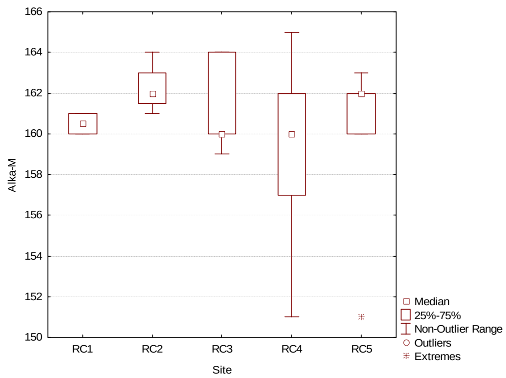
Water quality parameter data is plotted in the following graphs with data grouped by site. The lower and upper limits of the box represent the 25th and 75th percentiles, respectively; whiskers represent the non-outlier minima and maximaand; and the point in the center of the box represents the median value. Outliers are represented by circles, and extremes are represented by asterisks.

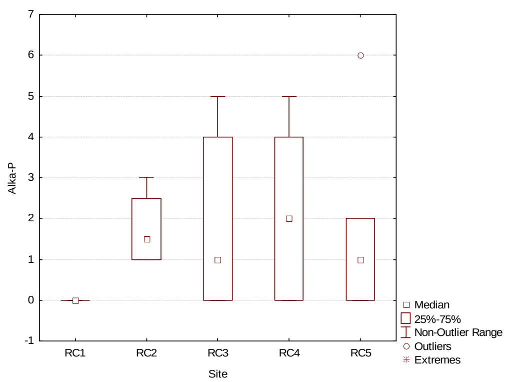


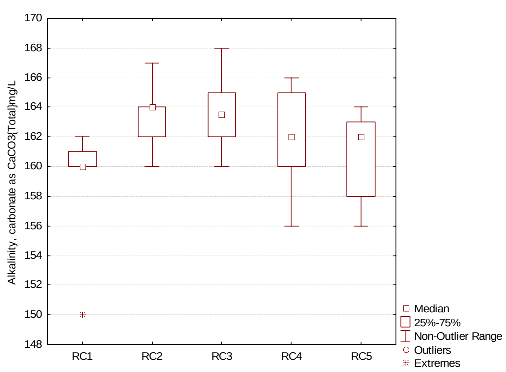


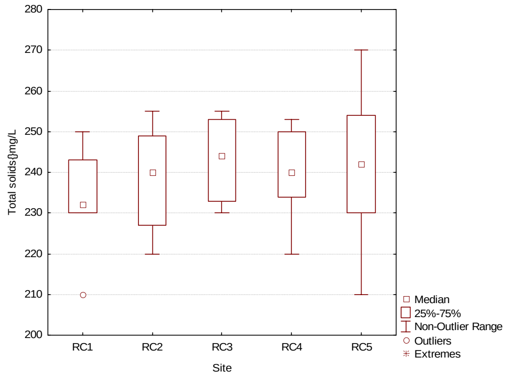



Specific Conductance()<F>umho/cm
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

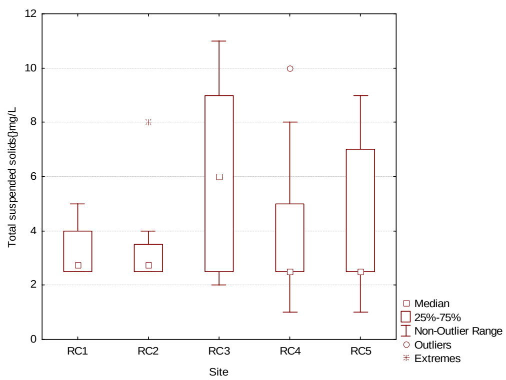

Alka-M
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes


Alka-P
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

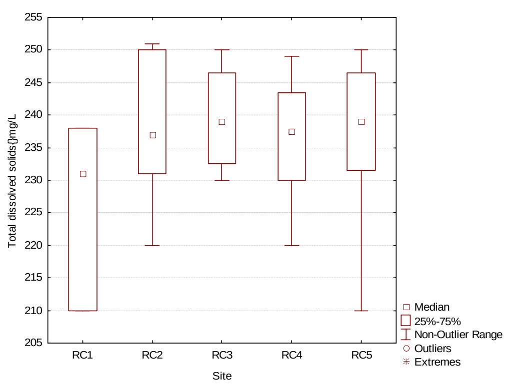

Alkalinity, carbonate as CaCO3(Total)mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes



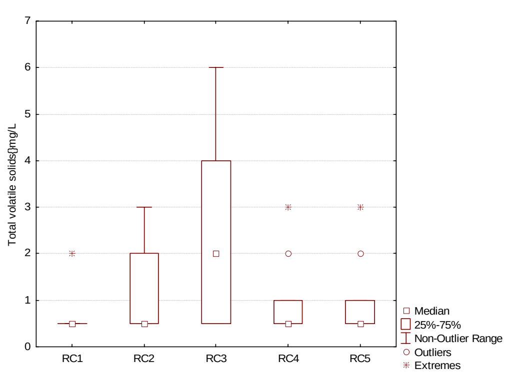
Total solids mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes



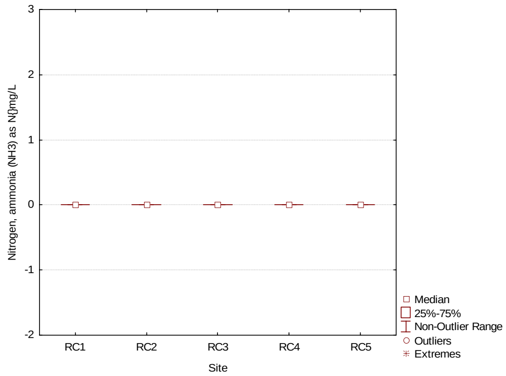
Total suspended solids mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

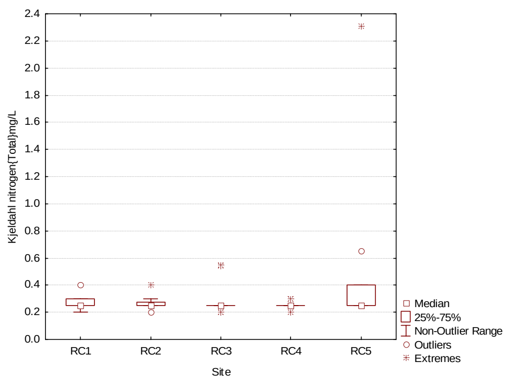


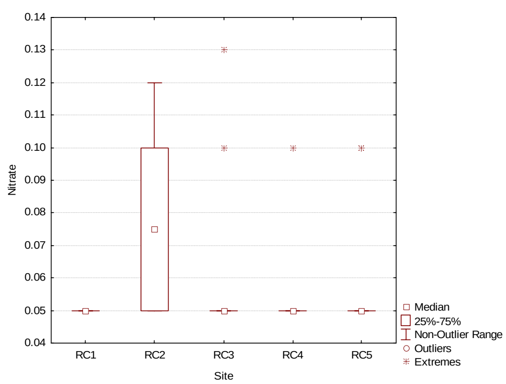
Total dissolved solids mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

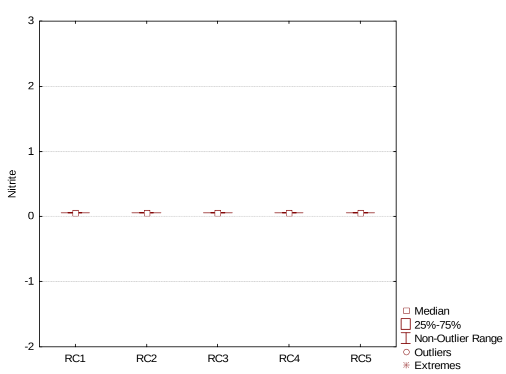


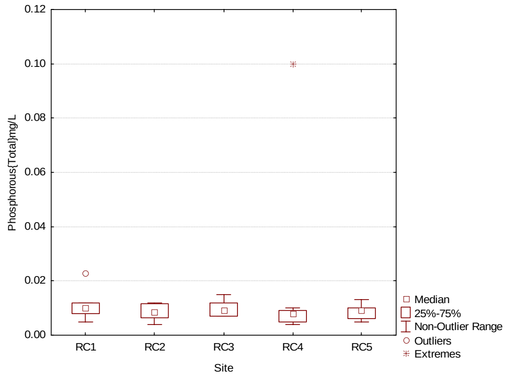
Total volatile solids mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes


Nitrogen, ammonia (NH3) as N[]mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

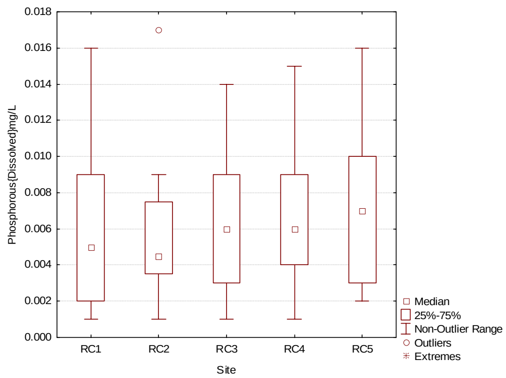

Kjeldahl nitrogen(Total)mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes


Nitrate
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

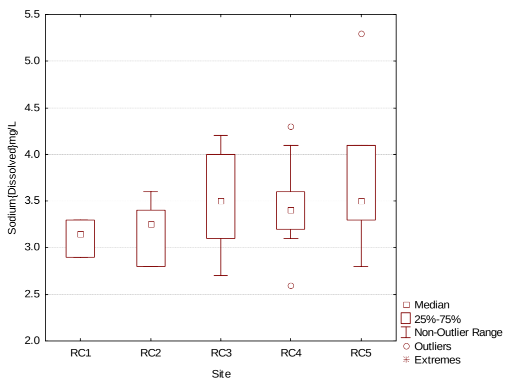

Nitrite
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes



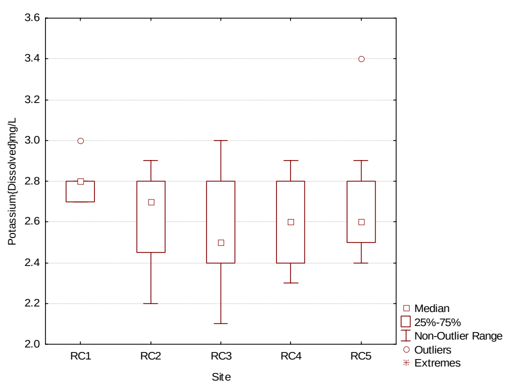
Phosphorous(Total)mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes



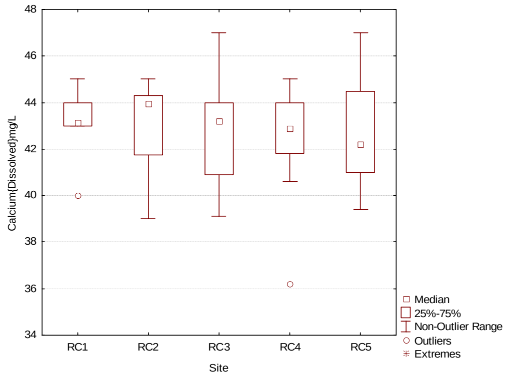
Phosphorous(Dissolved)mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

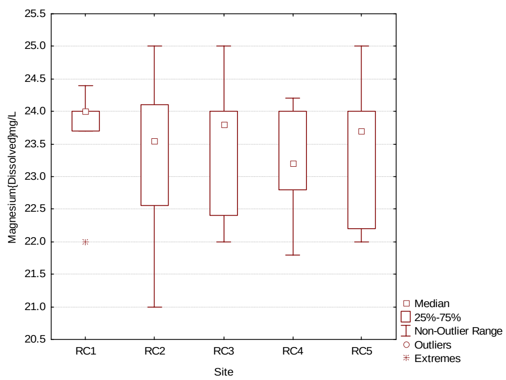


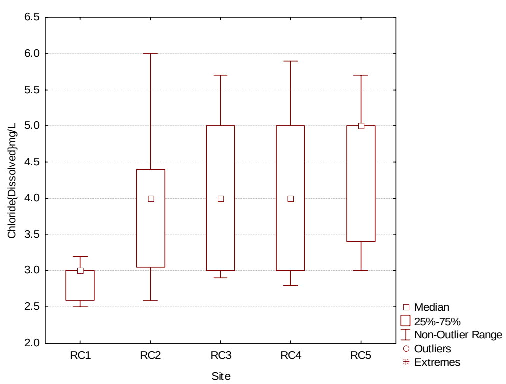
Sodium(Dissolved)mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

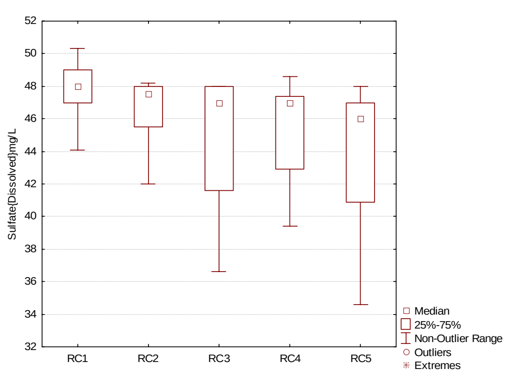


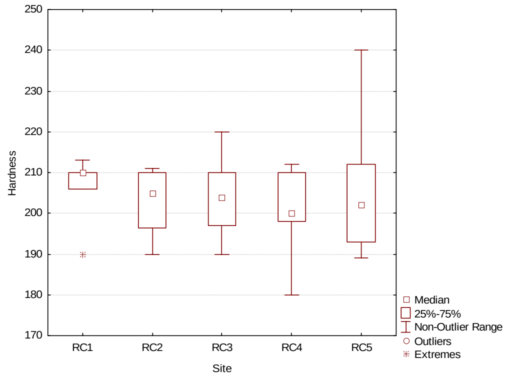
Potassium(Dissolved)mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

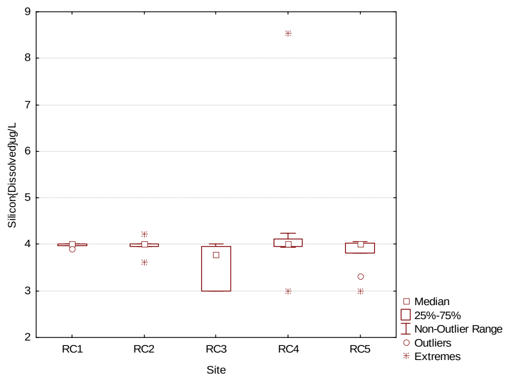

Calcium(Dissolved)mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

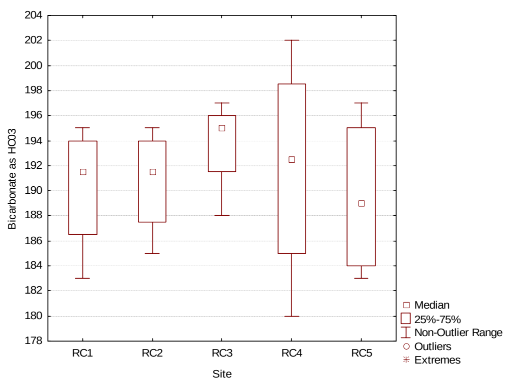

Magnesium(Dissolved)mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

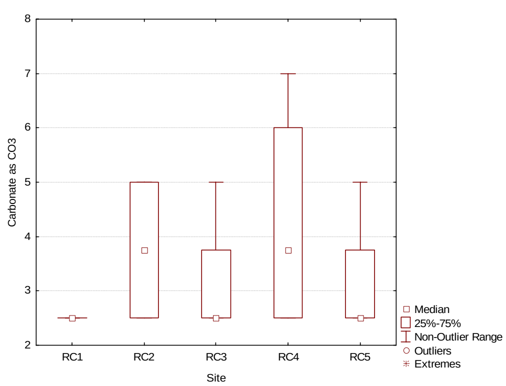

Chloride(Dissolved)mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes


Sulfate(Dissolved)mg/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes


Hardness
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes


Silicon(Dissolved)ug/L
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes


Bicarbonate as HCO3
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes


Carbonate as CO3
Site
RC1
RC2
RC3
RC4
RC5
Median
25%-75%
Non-Outlier Range
Outliers
Extremes